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NASALIFE—Component Fatigue and Creep Life Prediction Program

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Abstract

NASALIFE is a life prediction program for propulsion system components made of ceramic matrix composites (CMC) under cyclic thermo-mechanical loading and creep rupture conditions. Although, the primary focus was for CMC components the underlying methodologies are equally applicable to other material systems as well. The program references empirical data for low cycle fatigue (LCF), creep rupture, and static material properties as part of the life prediction process. Multiaxial stresses are accommodated by Von Mises based methods and a Walker model is used to address mean stress effects. Varying loads are reduced by the Rainflow counting method or a peak counting type method. Lastly, damage due to cyclic loading and creep is combined with Minor's Rule to determine damage due to cyclic loading, damage due to creep, and the total damage per mission and the number of potential missions the component can provide before failure.

1. Introduction

Engine companies are constantly striving to improve the performance and life of their gas turbine engines. Materials are pushed to new limits as new materials and concepts are applied to gas turbines to increase operating temperatures, reduce weight, and improve aerodynamic efficiencies. Also, there is the need to reduce maintenance costs and down time making life prediction with increased accuracy an important issue. The method of accurately determining the fatigue life of an engine component in service has become increasingly complex. This results, in part, from the complex missions which are now routinely considered during the design process. These missions include large variations of multiaxial stresses and temperatures experienced by critical engine parts.

NASALIFE was written in an attempt to provide a convenient software package to the designer for determining the life of a component under cyclic thermo-mechanical loading. The program was developed at General Electric Aircraft Engines (GEAE) under the National Aeronautics and Space Administration's (NASA) Enabling Propulsion Materials (EPM) program. The EPM program and its objectives were summarized by Brewer (1999) and NASALIFE was briefly covered by Levine, et al. (2000). NASALIFE was developed further by N&R Engineering under NASA's Ultra Efficient Engine Technology (UEET) program. It should be noted that NASALIFE is not a final and all inclusive program for predicting component life, but is the part of the continuing process to improve life prediction

techniques. Empirical data is used as a reference for predicting the fatigue life of a component. As a result, the definition of failure is the same as the failure criteria of the empirical data. This code utilizes specific methods which are intended to provide conservative life predictions. In some cases these may be excessively conservative. The lives predicted by NASALIFE should be examined carefully by the design engineer in view of engineering judgment and experience. The output information from NASALIFE has been designed to provide the design engineer a quick assessment of the most damaging portion of each cycle. It is the user's responsibility to seek guidance on correct choices or options for calculating life.

2. Technical Background

High temperature structural components of a gas turbine engine are placed under severe environmental conditions during engine operation. The components experience thermal cycling, body forces, and extraneous loads from the gas flow. In addition, there are issues with creep, corrosion, and erosion. The conditions can cause crack initiation and propagation through a component at highly stressed locations. The cracks, if undetected, would eventually result in the component failing to perform as required. NASALIFE is a tool which the engineer can use when combining operating conditions, heat transfer analysis, stress analysis, and materials data to establish the minimum predicted life to failure due to crack initiation or complete fracture.

NASALIFE requires as input a complete mission stress and temperature history. Stresses can be uniaxial or, in the case of isotropic materials, multiaxial. Also required for input are a number of material related data items, such as the appropriate family of pseudo-stress versus life curves, a Walker exponent, as presented by Walker (1970), and its variation with temperature determined for low cycle fatigue (LCF) applications, and the nonlinear stress-strain curve information. The program itself will then compute the major LCF cycle, identify all subsequent minor cycles, and finally produce a calculated LCF life for the given mission. All calculations in NASALIFE are performed using elastic stresses. In addition, NASALIFE can also estimate life relative to creep rupture and the combined life due to LCF and creep. Figure 1 shows a flow chart for NASALIFE.

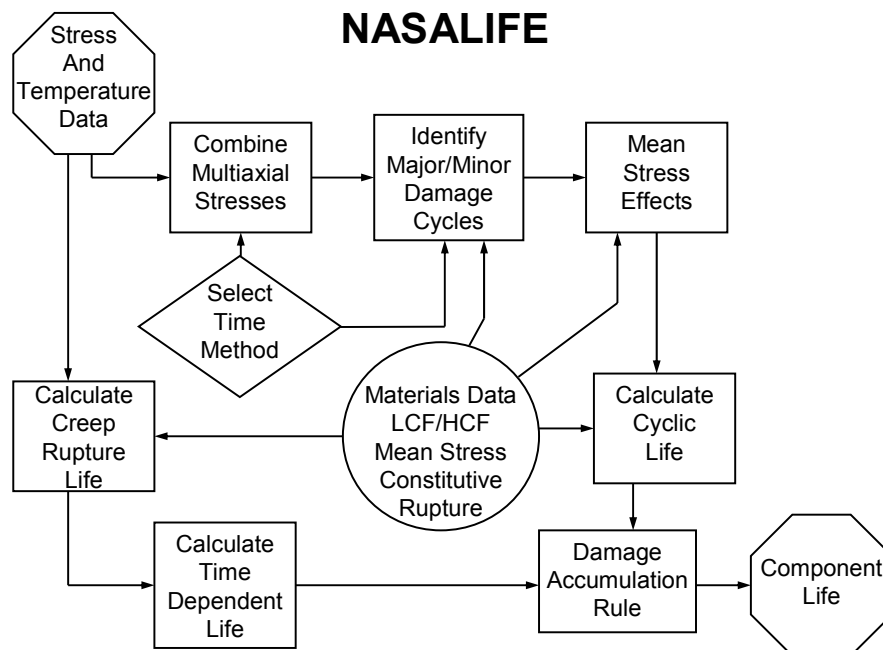


Figure 1.—A flow chart for NASALIFE.

2.1. LCF Data

The fatigue data input contains a series of values for stress and a corresponding life which describe a series of isothermal LCF curves. Extrapolation beyond either the maximum temperature or maximum stress of the fatigue data is not permitted and will be indicated by an error flag and assigned a life of zero cycles or missions. Also, the lowest temperature LCF data is used to determine failure when the mission temperature is below the lowest available data temperature. The LCF life is determined for a given stress amplitude by a log-log interpolation between adjacent stress-life points given in the data file. The interpolation between temperatures is performed in a linear fashion.

The fatigue data series of stress and corresponding life does not permit inclusion of an absolute endurance limit, so the last point in the file is the life for zero stress. This is necessary so that a life can be calculated for very small stress amplitudes. NASALIFE does not permit the termination life to exceed 10^{31} cycles due to exponent overflow errors. NASALIFE checks the selected data for the termination life and prints an error flag if the 10^{31} value is exceeded.

2.2. Multiaxial Fatigue Methods

Critical locations in engine components often experience significant multiaxial stress fields. The multiaxial stresses consist of the three orthogonal normal stresses, σ_x , σ_y , σ_z , and three shear stresses, τ_{xy} , τ_{yz} , τ_{zx} . Also, with a cyclic load there is a minimum stress and maximum stress per cycle which are indicated with the subscripts min and max, respectively. Figure 2 illustrates the load cycle and the variables to describe it. Multiaxial methods are used to convert the multiaxial stresses into an equivalent uniaxial stress. This conversion must include the treatment of both the mean stress, σ_m , and the stress amplitude, also referred to as the alternating stress, σ_a . The mean stress and the stress amplitude are defined by the following equations

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2}$$

$$\sigma_a = \frac{\sigma_{\max} - \sigma_{\min}}{2}$$
(1)

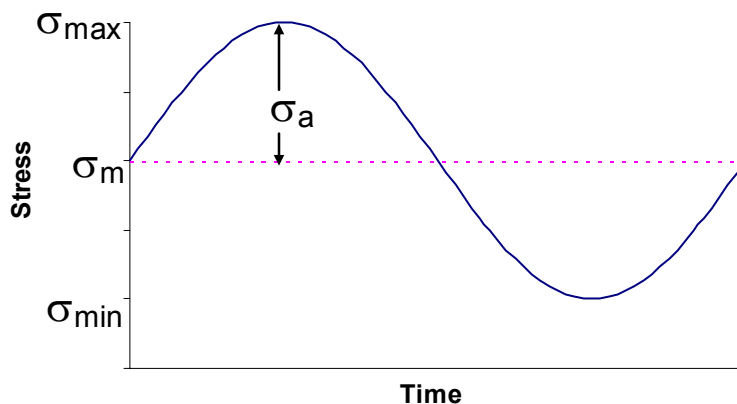


Figure 2.—The illustration shows the stress variables and subscripts to describe a load cycle.

Upon rearranging the above equations we have

$$\sigma_{\max} = \sigma_m + \sigma_a \quad (2)$$

$$\sigma_{\min} = \sigma_m - \sigma_a$$

Two other terms are commonly used for describing fatigue loads. These are the *R*-ratio, *R*, and the *A*-ratio, *A*, as defined by the following equations

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} \quad (3)$$

$$A = \frac{\sigma_a}{\sigma_m} \quad (4)$$

There are several methods described in the literature for calculating a single effective stress from the multiaxial stresses. A few of the methods are utilized in NASALIFE. In addition, the Manson-McKnight and Modified Manson-McKnight multiaxial stress methods are introduced here. The methods, used in NASALIFE, are based on the Von Mises method, also known as the octahedral shear stress method and distortion energy method. The multiaxial methods are restricted to proportional loading of the multiaxial stresses. Isotropic material properties are assumed. The subsequent sections describe the methods used within NASALIFE.

The following equations are used throughout the next section. These are the mean stresses and stress amplitudes in the orthogonal directions, *x*, *y*, and *z*.

$$\begin{aligned} \sigma_{xm} &= \frac{\sigma_{x \max} + \sigma_{x \min}}{2} & \sigma_{xa} &= \frac{\sigma_{x \max} - \sigma_{x \min}}{2} \\ \sigma_{ym} &= \frac{\sigma_{y \max} + \sigma_{y \min}}{2} & \sigma_{ya} &= \frac{\sigma_{y \max} - \sigma_{y \min}}{2} \\ \sigma_{zm} &= \frac{\sigma_{z \max} + \sigma_{z \min}}{2} & \sigma_{za} &= \frac{\sigma_{z \max} - \sigma_{z \min}}{2} \end{aligned} \quad (5)$$

Also, the shear stresses are defined as

$$\begin{aligned} \tau_{xym} &= \frac{\tau_{xy \max} + \tau_{xy \min}}{2} & \tau_{xya} &= \frac{\tau_{xy \max} - \tau_{xy \min}}{2} \\ \tau_{yzm} &= \frac{\tau_{yz \max} + \tau_{yz \min}}{2} & \tau_{yza} &= \frac{\tau_{yz \max} - \tau_{yz \min}}{2} \\ \tau_{zxm} &= \frac{\tau_{zx \max} + \tau_{zx \min}}{2} & \tau_{zxa} &= \frac{\tau_{zx \max} - \tau_{zx \min}}{2} \end{aligned} \quad (6)$$

As noted above, the subsequent sections describe the various Von Mises based methods available in NASALIFE. These methods are used to convert the multiaxial stresses to a single effective stress. The user decides which method is appropriate for the desired analysis, although, the program does use the Manson-McKnight method as the default method for reducing a multiaxial stress to a uniaxial stress.

2.2.1. The Manson-McKnight Method.—A method used in NASALIFE is known as the Manson-McKnight method. The equations for the mean stress and the stress amplitude of the Manson-McKnight method are described below:

$$\sigma_m = \text{SIGN}(\sigma_{xm} + \sigma_{ym} + \sigma_{zm}) \frac{\sqrt{2}}{2} \sqrt{(\sigma_{xm} - \sigma_{ym})^2 + (\sigma_{ym} - \sigma_{zm})^2 + (\sigma_{zm} - \sigma_{xm})^2 + 6(\tau_{xym}^2 + \tau_{yzm}^2 + \tau_{zxm}^2)} \quad (7)$$

$$\sigma_a = \frac{\sqrt{2}}{2} \sqrt{(\sigma_{xa} - \sigma_{ya})^2 + (\sigma_{ya} - \sigma_{za})^2 + (\sigma_{za} - \sigma_{xa})^2 + 6(\tau_{xya}^2 + \tau_{yza}^2 + \tau_{zxa}^2)} \quad (8)$$

The stress amplitude and the mean stress are defined by the Von Mises criteria. In addition, the mean stress is modified where the sign of the mean stress is the sign of the sum of the normal stresses with the use of the SIGN term.

The major limitation of this method is for cases which are dominated by shear stresses. Consider the plane stress case where a material is cycled under a normal stress and a proportional shear stress. The loads are

$$\begin{aligned} \sigma_{x \min} &= 0.0 \text{ ksi} & \tau_{xy \min} &= 0.0 \text{ ksi} \\ \sigma_{x \max} &= 0.1 \text{ ksi} & \tau_{xy \max} &= 100 \text{ ksi} \end{aligned}$$

The resulting stress amplitude and mean stress are

$$\begin{aligned} \sigma_a &= 86.6 \text{ ksi} \\ \sigma_m &= 86.6 \text{ ksi} \end{aligned}$$

If the sign is changed on the applied normal stress such that

$$\begin{aligned} \sigma_{x \min} &= 0.0 \text{ ksi} & \tau_{xy \min} &= 0.0 \text{ ksi} \\ \sigma_{x \max} &= -0.1 \text{ ksi} & \tau_{xy \max} &= 100 \text{ ksi} \end{aligned}$$

The resulting stress amplitude and mean stress are

$$\begin{aligned} \sigma_a &= 86.6 \text{ ksi} \\ \sigma_m &= -86.6 \text{ ksi} \end{aligned}$$

In this case, a change of 0.2 ksi results in a change of the mean stress by 173.2 ksi due to the SIGN term in the mean stress equation.

2.2.2. The Modified Manson-McKnight Method (Shaft Life Option).—The Modified Manson-McKnight method changes the sign calculation for the mean stress. The sign term, $\text{SIGN}(\sigma_{xm} + \sigma_{ym} + \sigma_{zm})$, of the Manson-McKnight mean stress equation is replaced with a function of the largest and smallest principal stresses, σ_1 and σ_3 , respectively for each loading condition. The principal stresses are found by solving for σ with the following determinant.

$$\begin{vmatrix} (\sigma_x - \sigma) & \tau_{xy} & \tau_{zx} \\ \tau_{xy} & (\sigma_y - \sigma) & \tau_{yz} \\ \tau_{zx} & \tau_{yz} & (\sigma_z - \sigma) \end{vmatrix} = 0 \quad (9)$$

The substitution is for the case when the sign of the largest principal stress, σ_1 , is different from the sign of the smallest principal stress, σ_3 . The function is as follows

$$\frac{\sigma_1 + \sigma_3}{\sigma_1 - \sigma_3}$$

The resulting equation for the mean stress is

$$\sigma_m = \frac{\sqrt{2}}{2} \sqrt{(\sigma_{xm} + \sigma_{ym})^2 + (\sigma_{ym} + \sigma_{zm})^2 + (\sigma_{zm} + \sigma_{xm})^2 + 6(\tau_{xym}^2 + \tau_{yzm}^2 + \tau_{zxm}^2)} * \left(\frac{\sigma_1 + \sigma_3}{\sigma_1 - \sigma_3} \right) \quad (10)$$

The stress amplitude remains the same as the one presented with the Manson-McKnight method. The equation for the stress amplitude is

$$\sigma_a = \frac{\sqrt{2}}{2} \sqrt{(\sigma_{xa} - \sigma_{ya})^2 + (\sigma_{ya} - \sigma_{za})^2 + (\sigma_{za} - \sigma_{xa})^2 + 6(\tau_{xym}^2 + \tau_{yzm}^2 + \tau_{zxa}^2)} \quad (11)$$

In the example used with the Manson-McKnight method where

$$\begin{array}{ll} \sigma_{x \min} = 0.0 \text{ ksi} & \tau_{xy \min} = 0.0 \text{ ksi} \\ \sigma_{x \max} = 0.1 \text{ ksi} & \tau_{xy \max} = 100 \text{ ksi} \end{array}$$

with the resulting stress amplitude and mean stress of

$$\begin{array}{l} \sigma_{\text{alt}} = 86.6 \text{ ksi} \\ \sigma_{\text{mean}} = 86.6 \text{ ksi} \end{array}$$

If the sign is changed on $\sigma_{x \max}$ so that $\sigma_{x \max} = -0.1$, these values would remain the same, that is

$$\begin{array}{l} \sigma_{\text{alt}} = 86.6 \text{ ksi} \\ \sigma_{\text{mean}} = 86.6 \text{ ksi} \end{array}$$

2.2.3. The Sines Method.—The Sines method, as noted by Sines and Ohgi (1981), calculates the mean stress as the sum of the mean stresses in each orthogonal direction as illustrated with the following equation

$$\sigma_m = \sigma_{xm} + \sigma_{ym} + \sigma_{zm} \quad (12)$$

In addition, the Sines method stress amplitude, σ_a , modifies the alternating stress derived from the distortion energy method. Here, the stress amplitude is also a function of a constant, C_1 , and the mean stress as illustrated in the following equation

$$\sigma_a = \frac{\sqrt{2}}{2} \sqrt{(\sigma_{xa} - \sigma_{ya})^2 + (\sigma_{ya} - \sigma_{za})^2 + (\sigma_{za} - \sigma_{xa})^2 + 6(\tau_{xya}^2 + \tau_{yza}^2 + \tau_{zxa}^2)} + C_1 \sigma_{\text{mean}} \quad (13)$$

The constant, C_1 , is assigned the following values under the given conditions within NASALIFE

$$C_1 = 0.5 \text{ for uniaxial loading conditions}$$

$$C_1 = 1.0 \text{ for multiaxial loading conditions}$$

Lastly, the Sines method adjusts the LCF data to A -ratio = ∞ . This theory implies that a mean shear stress has no effect on fatigue life.

2.2.4. The Smith Watson Topper Method.—The Smith-Watson-Topper (1970) method does not use the Walker mean stress model. The mean stress is assumed to be zero.

$$\sigma_m = 0 \quad (14)$$

The stress amplitude, σ_a , is a function of the largest principal stress, σ_1 with the Smith-Watson-Topper method. The maximum value of the largest principal stress, $\sigma_{1 \max}$, is calculated from stresses $\sigma_{x \max}$, $\sigma_{y \max}$, $\sigma_{z \max}$, $\tau_{xy \max}$, $\tau_{yz \max}$, $\tau_{zx \max}$. The minimum value of the largest principal stress, $\sigma_{1 \min}$, is calculated from the stresses $\sigma_{x \min}$, $\sigma_{y \min}$, $\sigma_{z \min}$, $\tau_{xy \min}$, $\tau_{yz \min}$, $\tau_{zx \min}$. The resulting equation for the stress amplitude is

$$\sigma_a = \frac{1}{2} \sqrt{\sigma_{1 \max} (\sigma_{1 \max} - \sigma_{1 \min})} \quad (15)$$

2.2.5. The R-Ratio Sines Method.—The R -ratio Sines method uses the mean stress from the Sines method presented above. The equation for the mean stress is

$$\sigma_m = \sigma_{xm} + \sigma_{ym} + \sigma_{zm} \quad (16)$$

The stress amplitude, σ_a , calculation, similar to the distortion energy method, is

$$\sigma_a = \frac{\sqrt{2}}{2} \sqrt{(\sigma_{xa} - \sigma_{ya})^2 + (\sigma_{ya} - \sigma_{za})^2 + (\sigma_{za} - \sigma_{xa})^2 + 6(\tau_{xya}^2 + \tau_{yzm}^2 + \tau_{zxa}^2)} \quad (17)$$

2.2.6. Effective Method.—The Effective method, presented here, derives its mean stress by doubling the mean stress from the distortion energy method and reducing it by the magnitude of the stress amplitude. The equation for the mean stress follows

$$\sigma_m = \sqrt{2} \sqrt{(\sigma_{xm} + \sigma_{ym})^2 + (\sigma_{ym} + \sigma_{zm})^2 + (\sigma_{zm} + \sigma_{xm})^2 + 6(\tau_{xym}^2 + \tau_{yzm}^2 + \tau_{zxm}^2)} - \sigma_a \quad (18)$$

The Effective method determines the scalar stress amplitude, σ_a , from the distortion energy method, that is the same as the one presented with the Manson-McKnight method. The equation for the stress amplitude is

$$\sigma_a = \frac{\sqrt{2}}{2} \sqrt{(\sigma_{xa} - \sigma_{ya})^2 + (\sigma_{ya} - \sigma_{za})^2 + (\sigma_{za} - \sigma_{xa})^2 + 6(\tau_{xya}^2 + \tau_{yza}^2 + \tau_{zxa}^2)} \quad (19)$$

2.2.7. Other Methods.—New subroutines can be added to future versions of NASALIFE to accommodate different stress reduction methods.

2.3. The Walker Mean Stress Model

Most components operate with a varying mean stress occurring during their cyclic mission. There may be purely elastic mean stress effects due to the complex missions, or there may be a mean stress which is generated by local plastic yielding at sharp stress concentrations. The Walker (1970) model may be used in NASALIFE to address the influence of mean stresses on fatigue lives. To reiterate, NASALIFE only treats elastic stresses.

It was noted in the previous section but the parameters designated by R -ratio, R , and A -ratio, A , are commonly used to describe the level of mean stresses or stress. Reiterating, if we use stress as the parameter,

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} \quad (3)$$

$$A = \frac{\sigma_a}{\sigma_m} \quad (4)$$

or upon substituting variables, we get

$$R = \frac{\sigma_m - \sigma_a}{\sigma_m + \sigma_a} \quad (19)$$

$$A = \frac{\sigma_{\max} - \sigma_{\min}}{\sigma_{\max} + \sigma_{\min}} \quad (20)$$

Also, it can be shown that

$$R = \frac{1 - A}{1 + A} \quad (21)$$

$$A = \frac{1 - R}{1 + R} \quad (22)$$

For example, most specimen testing is with the minimum stress, σ_{\min} , at zero and the maximum stress, σ_{\max} , greater than zero resulting in $R = 0$ and $A = 1$. With the R -ratio being zero the stress amplitude is one half of the maximum stress.

The Walker equation can be presented for the modified stress amplitude or Walker stress amplitude, σ_{aw} , as a function of the maximum stress; R -ratio; and the Walker exponent, m . The equation is

$$\sigma_{aw} = \frac{1}{2} \sigma_{\max} (1 - R)^m \quad (23)$$

For fatigue lives, this expression is converted to a function of the stress amplitude using the identity:

$$\sigma_{\max} = 2 \frac{\sigma_a}{1 - R} \quad (24)$$

Substitution of the maximum stress, σ_{\max} , into the equation for the Walker stress amplitude, σ_{aw} , equation and rearranging results in

$$\sigma_{aw} = \sigma_a (1 - R)^{(m-1)} \quad (25)$$

This approach results in increased damage for $R > 0$ ($A < 1$), life benefit when $R < 0$ ($A > 1$), and no effect when $R = 0$ ($A = 1$).

2.3.1. Walker Exponents Within NASALIFE.—One of the major difficulties with using the Walker mean stress model is the unavailability of Walker exponents. If Walker exponents have not been determined for a particular condition, then default Walker exponents can be invoked in NASALIFE. The default values with the given loading conditions are

$$m = 1.0 \text{ when } R < 0 \text{ and as a result } A > 1.0$$

$$m = 0.5 \text{ when } R \geq 0 \text{ and as a result } A \leq 1.0$$

The Walker modified stress amplitude is the same as the applied stress amplitude when the default Walker exponent, m , is 1.0 when the minimum stress is negative. When $R \geq 0$ the use of $m = 0.5$ results in lower lives relative to the use of the stress amplitude. If the life of a component is low when the default Walker exponents are used, it may be possible to increase the life using Walker exponents determined from experimental data.

NASALIFE reads temperature dependent Walker exponents from the materials data and interpolates values linearly with temperature. When the Walker exponents are not known, a value less than -1 should be entered in the material to invoke the use of default Walker exponents. No extrapolation is permitted outside the temperature range in the material's data.

2.3.2. Restrictions on the Walker Mean Stress Model.—Two restrictions have been placed on the use of the Walker model:

- (1) No additional benefit will be taken when the mean stress is negative.

The first restriction is based on the frequently observed behavior in LCF curves that little to no improvement in life will occur in test specimens with mean stresses less than zero, that is $R < -1$ ($A < 0$), relative to mean stresses greater than or equal to zero, $R \geq -1$ ($A \geq 0$), tests. This approach permits taking benefit for the mean stress effects up to mean stresses of zero, but does not permit any additional benefit.

- (2) When the stress amplitude exceeds yield, the higher of σ_a or σ_{aw} will be used to assess life. This is why the user inputs the stress strain curve.

2.3.3. A-Ratio Correction.—The A -ratio is initially assumed to be one or $R = 0$ for the LCF data within NASALIFE. If the value for the A -ratio is other than one then NASALIFE corrects the Walker calculation. NASALIFE adjusts the A -ratio when $A \leq 0.900$. The adjusted Walker calculation is

$$\sigma_{aw} = \sigma_a \left(\frac{1+A}{2A} (1-R) \right)^{m-1} \quad (26)$$

The A -ratio, A , is taken from the test conditions used to generate the LCF data that is used with NASALIFE. Under the condition that the A -ratio is less than or equal to zero, or greater than 10^7 then the term $(1+A)/2A$ is set to $1/2$, the value for $A = \infty$, such that the equation becomes

$$\sigma_{aw} = \sigma_a \left(\frac{1}{2} (1 - R) \right)^{m-1} \quad (27)$$

2.4. Load Cycle Counting Methods

The application of a varying load over time requires the use of a technique for counting the different cycles. This section describes the methods available in NASALIFE.

2.4.1. Rainflow Counting.—The simplest method of considering the full damage content of a mission is through the use of a rainflow counting technique as presented by Endo (1967, 1968). The rainflow counting technique is a standardized cycle counting method as per American Society for Testing and Materials (ASTM) (2004) E 1049–85. A common rainflow approach is to use the effective stress at the end points of a particular cycle. This will properly calculate the magnitude of the stress amplitude, but does not take into account the influence of the mean stress of the cycle or the variation of temperature during the cycle. As a result, NASALIFE uses a damage rainflow approach.

Damage counting schemes identify the most damaging cycle based on the stress and temperature data. In NASALIFE, a damage counting algorithm is used to identify the most damaging major cycle. The most damaging major cycle is determined by evaluating every combination of mission points, $N*(N-1)$ permutations for N mission points, to find the combination which will produce the lowest life. The life for each subcycle is calculated using the multiaxial method (section 2.2), and the mean stress model (section 2.3). All subsequent minor cycles are then identified using the more traditional stress rainflow techniques.

This damage rainflow approach can select any point in a mission, not necessarily a maximum or minimum stress. A good example of this would be a relatively slow loading ramp where the temperature goes through a large maximum. If the fatigue life of the material in question decreases with increasing temperature, an intermediate stress point at a high temperature might be one of the points in the most damaging cycle.

2.4.2. Rainflow Stresses.—NASALIFE reduces stress tensors to scalar values in preparation for applying the rainflow counting method. The program uses one of the previously described methods for reducing a multiaxial stress state to an effective uniaxial stress state along the maximum octahedral shear stress axis. As noted earlier, material isotropy is assumed. The rainflow counting method is used to reduce a complex variable amplitude mission loading to a more manageable effective mission loading. The method finds the most damaging cycles.

2.4.3. Rainflow Process.—NASALIFE uses a 6 step process:

1. Use a multiaxial method with a mean stress model and find the most damaging cycle of each mission and the most damaging mission.
2. The stress range for the most damaging cycle of the most damaging mission is used to identify the orientation which produces the maximum octahedral shear stress.
3. All 6 components of stress for each mission point of all missions are resolved into the critical plane and the component in the direction of the maximum octahedral shear stress direction is saved for all subsequent minor cycle identification.
4. A rainflow counting procedure is applied to the mission stresses to eliminate intermediate stress points and to pair the appropriate minimum and maximum stress points. Eliminate small cycles based on a tolerance of the largest applied stress in the mission.
5. The multiaxial fatigue method, and the mean stress model is then used to calculate the effective stress for each paired subcycle. The paired cycles are sorted on the minimum life, the maximum Walker stress and then the input order.

6. If the first two points from step 5 are not the same ones identified as the most damaging cycle in Step 1, these points are replaced with the most damaging cycle identified in step 1. This process may reduce the life relative to that determined for a pure stress rainflow analysis.

2.5. Cumulative Fatigue Damage

The fatigue life for a particular stress can be determined from the appropriate LCF curve. The durability life for the mission is obtained by combining the LCF damage of each of the individual cycles. NASALIFE estimates the LCF damage using Miner's (1945) rule:

$$\frac{1}{N} = \sum_i \frac{X_i}{N_i} \quad (28)$$

where X_i is number of cycles of one magnitude and environmental condition and N_i is the life with those cycles at the same environmental condition.

2.6. Rupture Calculations

NASALIFE will provide a calculated rupture life if rupture data is included in the input file. The stresses are converted from tensors to scalars using effective stress. A very simple integration over the mission is then performed. The step size is determined based on the larger of the time increment or the stress increment.

Rupture time is calculated for each increment. The rupture data may either be tables of temperature and stress versus life, or Larson-Miller (1952) parameters.

2.6.1. Larson-Miller Parameter for Creep.—The basic Larson-Miller equation is:

$$P = T(C + \log t) \quad (29)$$

where:

T temperature

C material constant

t time

P Larson-Miller parameter

The Larson-Miller parameter is a function of the log of the stress. For NASALIFE the Larson-Miller parameter is entered as a polynomial function of stress with simple adjustments as presented by Conway (1969). As a result, it is assumed that the Larson-Miller parameter has a normal distribution or, equivalently, the rupture time follows a lognormal distribution as noted by Zuo, et al. (2000).

NASALIFE uses the above equation solved for time as shown by the following equation

$$t = 10^{\left(\frac{P}{T} - C\right)} \quad (30)$$

It was noted above that the Larson-Miller parameter is entered as a polynomial function. The function is illustrated below

$$P = P_0 + P_1\sigma + P_2\sigma^2 + \dots + P_i\sigma^i \quad (31)$$

where:

P_i polynomial coefficients
 σ applied effective stress

2.7. Combined LCF and Rupture Life

In NASALIFE, the total damage caused by a mission is the sum of the damage due to cyclic fatigue and the damage due to creep. Damage is the life used by a mission divided by the total available life. As a result, damage that is greater than or equal to unity constitutes failure. Initially the life is determined for the creep life under a given loading condition. Damage, D_{creep} , is taken as the inverse of the life, L_{creep} as shown by the following equation

$$D_{creep} = \frac{1}{L_{creep}} \quad (32)$$

Also, NASALIFE converts the LCF life, L_{LCF} , to LCF damage, D_{LCF} , as illustrated by the equation below

$$D_{LCF} = \frac{1}{L_{LCF}} \quad (33)$$

The total damage, D , is

$$D = D_{LCF} + D_{creep} \quad (34)$$

NASALIFE can utilize an exponential creep damage rate leading to the following equation

$$D = D_{LCF} + D_{creep}^b \quad (35)$$

where b is the exponent for the creep damage.

2.8. Stress-Strain Properties

NASALIFE uses the Ramberg-Osgood (1947) curve fitting method for modeling the stress-strain curve of a material. As described by Dowling (1999) the Ramberg-Osgood method considers the elastic and plastic strain separately and sums them. The elastic strain is linearly related to the stress while the plastic strain has the exponential relationship with the stress. The equation is

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K} \right)^{\frac{1}{n}} \quad (36)$$

The variables for the above equation are defined as

σ stress
 ε strain
 E Young's modulus

- K Ramberg-Osgood constant
 n Ramberg-Osgood exponent

The Ramberg-Osgood constant, K , is the value of the stress, σ , at the initiation of plastic strain, ϵ_y . With strain at the initiation of yielding the above equation becomes

$$\sigma_y = K \epsilon_y^n \quad (37)$$

At the current time NASALIFE uses the material constants and Ramberg-Osgood parameters to calculate a 0.2 percent offset yield strength as the cutoff point for the Walker mean stress model. NASALIFE performs a linear interpolation on the constants K , and n with temperature. Extrapolation beyond the maximum temperature is not permitted and will be indicated by an error flag.

2.9. Other Issues Not Included In NASALIFE

Design engineers must often consider factors other than those discussed in this document in determining the fatigue life of their components. Some of these issues are:

- Time dependent deformation
- LCF/HCF Interaction
- Role of feature testing
- Composite material failure mechanisms
- An elastic plastic Walker model

These factors may be important, but until methods are established and verified for these they will not be included in NASALIFE. When those methods are developed, they will be included in future releases and the corresponding updated manual.

Another failure issue, particularly, with CMCs is pesting as presented by Ogbuji (2002). Pesting is the oxidative degradation of CMCs in a service environment at intermediate temperatures. As mentioned above as models become available they can be incorporated into NASALIFE.

3. User Manual

This section provides the information necessary for creating a mission input file and using NASALIFE. The mission file consists of keywords, flags, and data describing desired outputs, material properties, and loading conditions. The mission file uses keywords placed on the first line of each section with flags, parameters, or data on the following lines. Delimiters may consist of a space, comma, or ampersand. The program uses a free format entry method. The program will accept lower and upper case letters for the keywords. Any lower case alpha characters are converted to upper case within the program.

3.1. Output and Print Options

NASALIFE sets up the desired output with the print command, PRIN. The command line is followed by a line of ten numeric flags to set options. An example is shown below

```
PRIN
3 1 1 0 0 2 2 2 2 1
```

The first option has four choices as follows

- 0 Only the mission fatigue life and flags are printed to the terminal screen. No information is printed to an output file.
- 1 The fatigue life and flags are printed to the terminal screen. The mission rainflow, times, stresses, temperatures, life, and flags are printed to an output file.
- 2 The mission rainflow, times, stress, temperatures, life, and flags are all printed to the terminal screen and to an output file.
- 3 or greater The mission rainflow, times, stress, temperatures, life, and flags are all printed to an output file.

When results are directed to an output file NASALIFE creates an output file that uses the input file's name but replaces the input file's extension with the extension of ".out". If the input file name does not have an extension then NASALIFE just appends the ".out" extension on to the input file name for the output file. In the case an output file exists with the same name the program prompts the user to quit the run or overwrite the file with a new output file. NASALIFE uses the input file's drive and directory location for the output file.

The remaining 9 numeric print flags and their respective options are

Flag 2 is for file names

- 1 print file names
- not 1 do not print file names

Flag 3 is for mission echo

- 0 do not echo mission data
- not 0 echo mission data

Flag 4 is for critical damage plane information

- 0 no critical damage plane information printed
- greater than 0 critical damage plane information printed

Flag 5 is for rainflow/mission edit information

- 0 rainflow/edit information suppressed
- not 0 rainflow/edit information printed

Flag 6 is for rupture data

- 0 no rupture data printed
- 1 reserved
- 2 or greater print rupture data

Flag 7 is for LCF data

- 0 no LCF data printed
- 1 reserved
- 2 or greater print LCF data

Flag 8 is for material file data

- 0 no material data is printed
- not 0 material data is printed

Flag 9 is for minor load cycle printout

0	no information on minor cycles printed
1	reserved
2 or greater	information on minor cycles printed

Flag 10 is for program options

0	No internal stress handling information printed
not 0	Internal stress handling information printed

3.2. Material Data

NASALIFE references material and mechanical properties data as part of the life prediction process. The data is usually empirically derived. The properties include LCF data, creep rupture data or Larson-Miller parameters for creep, and static properties. The following sections described the format for entering the data in the mission file.

One important restriction is that no extrapolations beyond values defined in the input file are permitted. Any extrapolations to a higher or lower temperature or to a higher stress will result in a life of 0.1 for that cycle, resulting in a negligible life for the entire mission. Therefore, the reference data utilized must cover the entire range of temperatures and stresses for the mission being analyzed. This safeguard has been placed in the code so that data base extrapolations and/or issues are performed by the appropriate engineering personnel and not arbitrarily performed in NASALIFE.

NASALIFE does not contain a model for matching an LCF curve with an endurance limit. The program provides a finite life for low amplitude loading cycles. In addition, lives beyond 10^{31} cycles are not permitted due to difficulties with exponential overflow. Lives longer than 10^{31} cycles will be assumed to have a life of 10^{31} cycles.

3.2.1. LCF Properties Data.—NASALIFE requires LCF data as a reference for estimating life under various loads. The LCF properties are the maximum stress and the resulting life at various temperatures and a given *A*-ratio. The LCF data entry is selected with the keyword LCF followed by other keywords and their respective information and the actual LCF data. As described in previous sections the keyword is placed on one line followed by the required information on the next line.

The keys used under the LCF command are

TITL LCF data title

ARAT *A*-ratio (stress amplitude or alternating stress divided by mean stress) by which LCF data was generated

FLIF SMAX FLAG TEMP

where

FLIF	life in cycles
SMAX	Maximum stress in ksi
FLAG	described below
TEMP	temperature in °F

The keywords, FLIF, SMAX, FLAG, and TEMP can be in any order within the line. The data following the command line has to be in the same order as the keywords within the keyword line.

EOF Line to indicate the end of LCF data section

NASALIFE calls for some restrictions in the LCF data. The restrictions are as follows

- Data is in order of increasing temperature.
- Next, data is in order of increasing life.
- At least two stress levels are required at each temperature.
- The LCF data set can only be at one *A*-ratio.

The flags determine the validity and applicability of the LCF data for a given mission. If this information is important to the quality of the analysis, information will be printed in the NASALIFE output. The flags are defined with a three digit integer (X1 X2 X3). The integers are not separated by delimiters. A single digit entry would set X1 and X2 to zero with X3 set to the given single digit entry. Similarly, a two digit entry sets X1 to zero and X2 and X3 to the given values. The values for the integers are as follows

Deviation flag (X1)

0	No deviation required
1	Deviation required

Temperature Extension Flag (X2)

0	within valid range of data
1	extended to high temperature outside data
2	extended to low temperature outside data

Stress amplitude Extension Flag (X3)

0	within valid range of data
1	extended to low stress amplitude outside data
2	extended to high stress amplitude outside data

An example of the LCF data section is presented below

```
LCF
TITL
Example NASALIFE LCF data
ARAT
1
FLIF SMAX FLAG TEMP
  1000 400 20 60
 10000 51 20
100000 50 121
  1000 300 0 300
 10000 21 0
100000 20 0
  1000 300 0 1000
 10000 21 0
100000 20 0
  1000 300 12 1300
 10000 11 10
100000 10 11
EOF
```

The flag, 20, in the example above is read as 020. The blanks in the temperature column lead the program to use the previous temperature.

3.2.2. Static Material Properties.—NASALIFE requires static material properties. The material properties consist of stress and strain deformation data at different temperatures. The program is informed of the initiation of the material data entry section with the keyword MATL followed by other relevant keywords and information and, finally, the material data. Keywords in the material section are as follows:

TITL	material title
CURV	curve number
GS	grain size
RKT	thermal conductivity, Kt
MATN	material data set number
FORM	material form
RORI	material orientation
ILIF	type of life data

Many of the above keywords are used to describe the material for the user. As a result, they are optional. The keyword, TITL, is to be by itself in a line with the actual title of the material section on the next line. The remaining keywords can be placed on a single line with the respective values in the same order on the next line.

In addition, the following commands set options within the program.

IOP1	uniaxial mean stress option
0	.02 percent strain used for yield stress
1	0.2 percent strain used for yield stress (default)
IOP2	material option (unused)
IOP3	material option (unused)
IOP4	material option
0	program does not allow low temperature extrapolation (default)
1	allow low temperature extrapolation
IOP5	material option (unused)

TEMP M FLAG walker exponent data where
 TEMP is temperature in °F
 M is the Walker exponent
 FLAG is described further down below

TEMP E K N V FLAG are stress-strain data (*E* and *V* are ignored at this time) where
 TEMP is temperature in °F
E is Young's modulus of elasticity in ksi
K is the Ramberg-Osgood constant
N is the Ramberg-Osgood exponent
V is Poisson's ratio
 FLAG is described further down below:

EOF end of material data key

Default values for the Walker exponent are activated by using any value less than of -1 with the exponent keyword, *M*. As noted earlier in the theoretical section, the default Walker exponent, *m*, is

$$m = 1 \text{ when } R < 0, A > 1$$

$$m = 0.5 \text{ when } R \geq 0, A \leq 1$$

All data must be represented in units of °F and KSI.

The input options for the keyword, FLAG, are

000 = valid regime
 010 = extrapolated to high temperature
 020 = extrapolated to low temperature

The options for the keyword, ILIF, are

0 for 95/99 curve
 1 for three standard deviations curve
 2 for average properties

No extrapolations beyond values defined in the input files are permitted. Any extrapolations to a higher or lower temperature will result in a life of 0.1, resulting in a negligible life for the entire mission. Therefore, the materials data must cover the entire range of temperatures for the mission being analyzed.

The following lines demonstrate the material entry section

```
MATL
TITL
Example NASALIFE material file
IOP1 IOP2
  1  1
TEMP M FLAG
  60 .5 20
 1300 .5 10
TEMP  E  K  N  V FLAG
  60 30000 100 0 .3 20
 1300 30000 100 0 .3 10
EOF
```

3.2.5. Creep Rupture Information.—The use of creep rupture information in the input file for NASALIFE is optional. If creep rupture information is available then NASALIFE will calculate the life due creep and the combined effects of LCF and creep. Creep rupture data may be entered as a table of empirical data or in equation form. Entry of tabular form of creep rupture data is initiated with the keyword, RUPT. Alternatively, creep rupture information may be entered with Larson-Miller parameters. The Larson-Miller equation form of data entry is initiated with the keyword, RUPD.

First, the method for entering creep rupture information using Larson-Miller parameters is covered here. As noted, the keyword, RUPD, is used to initiate equation parameters entry for creep rupture behavior. The keys that follow are:

TITL material title
 REXP the rupture damage exponent (used with summing of damage)
 SOFF stress offset
 ISTY stress type for applying the stress offset

$$0 \quad \sigma = \log \sigma - \sigma_{\text{offset}}$$

$$1 \quad \sigma = \sigma - \sigma_{\text{offset}}$$

TADD temperature adder or offset (default 459.67 for °F to °R)

TMUL temperature multiplier for converting to Rankine (default 1.)

NASALIFE is setup to read temperature in degrees Fahrenheit. Internally, the program converts the temperature to Rankine. In the event other units for temperature are provided the keywords, TMUL and TADD, can be included for the program to convert the given temperatures to units of Rankine. The program uses the following equation for the conversion

$$T_{\text{Rankine}} = (T + \text{TADD})\text{TMUL}$$

The following table provides values for TADD and TMUL that should be used with the given data temperature units

data units	TADD	TMUL
°F	459.67	1.00
°C	273.15	1.80
°R	0.00	1.00
K	0.00	1.80

The entry of the Larson-Miller parameter polynomial coefficients is initiated with the keyword, PM. The lines following the keyword line include the coefficients with one coefficient per line. The example at the end of this section illustrates a Larson-Miller polynomial and its entry in a mission file.

The Larson-Miller parameter can be set to change upon exceeding a threshold temperature. The program will look for the change with the keyword, LMFM and its value set to one.

LMFM—Larson-Miller form

0 for no change in the Larson-Miller parameter polynomial with temperature (default)

1 for change upon exceeding a threshold temperature

The Larson-Miller parameter varies exponentially with temperature and user defined constants upon exceeding the threshold temperature. The keywords for the constants are

PTEM temperature above which the exponential form of the Larson-Miller parameter becomes active

PBAS base for the exponential component

PEXP exponent

The equation form being

$$P_{\text{modified}} = P + \text{PBAS}(T - T_{\text{threshold}})^{\text{PEXP}}$$

The modified Larson-Miller parameter can be further modified. The following equation is used

$$P_{\text{modified } 2} = P_{\text{modified}} + \text{PAVG} * T$$

The above equation becomes active with the keyword, IRUP, and its value set at 1. This in addition to the first modified Larson-Miller being active. Also, the constant PAVG is entered with the keyword of the same name followed by its value in the next line.

PAVG minimum to average factor

Other parameters for the Larson-Miller equation are as follows

C Larson-Miller constant
 RMUL rupture time multiplier
 TMLO the low temperature for this equation
 TMHI the high temperature for this equation
 STLO the low stress for this equation
 STHI the high stress for this equation
 EOF end of rupture equation key

A user defined adjustment to the rupture life may be entered into NASALIFE. The keyword for the multiplier is RMUL with its value on the following line. The multiplier adjusts the Larson-Miller equation as illustrated by the following equation

$$t = 10^{\left(\frac{P}{T} - C\right) * \text{RMUL}}$$

These all default to zero. TMHI and STHI should be greater than zero for the equation format to work. Temperatures below TMLO and stresses below SMLO will be converted to the low value before calculating the life.

The following lines provide an example for entering creep rupture equation data. The polynomial form of the Larson-Miller parameter, P , for the example is

$$P = 40 - 15\sigma - 7\sigma^2$$

```
RUPD
TITL
Example NASALIFE creep rupture equation data
TMLO TMHI STLO STHI C   SOFF  TMUL  TADD
1200 1300  55  150 20   2.00  1    459.67
PM
40
-15
-7
EOF
```

As noted at the beginning of this section, creep-rupture data may be entered as a table of empirical data or in equation form. This section covers data entry in tabular form. The key, RUPT, is used to initiate the entry of creep-rupture information within the mission file. The keys that follow are:

TITL material title
 REXP rupture damage exponent
 IRUP flag: 1 average, 2 minimum
 RLIF RSTR FLAG TEMP creep-rupture data where
 RLIF life in hours
 RSTR rupture stress in ksi
 FLAG described below
 TEMP temperature in °F
 EOF end of rupture table key

As with the LCF data NASALIFE calls for some restrictions with the creep rupture data. The restrictions are as follows

- Data is in order of increasing temperature
- Next, data is in order of increasing life
- Resulting stress must be in decreasing order

The rules for the flags are similar to the ones presented with the LCF data entry section. The flags determine the validity and applicability of the rupture data for a given mission. If this information is important to the quality of the analysis, information will be printed in the NASALIFE output. The flags are defined with a three digit integer (X1 X2 X3). The integers are not separated by delimiters. A single digit entry would set X1 and X2 to zero with X3 set to the given single digit entry. Similarly, a two digit entry sets X1 to zero and X2 and X3 to the given values. The values for the integers are as follows

Deviation flag (X1)

0 No deviation required
 1 Deviation required

Temperature Extension Flag (X2)

0 within valid range of data
 1 extended to high temperature outside data
 2 extended to low temperature outside data

Stress Extension Flag (X3)

0 within valid range of data
 1 extended to low stress outside data
 2 extended to high stress outside data

Rupture data is interpolated linearly in stress, log in Rankine temperature, and log in life. Temperatures and stresses below the table values will be raised to the appropriate minimum table value. Temperatures and stresses above the table values will generate 10^{-31} for the life used.

An example of the rupture data section of the mission file is presented here

RUPT
 TITL
 Example NASALIFE creep rupture data
 IRUP
 1
 RSTR RLIF TEMP FLAG

150.000	239.269	1200.00	0
145.000	341.125	1200.00	0
140.000	490.251	1200.00	0
135.000	710.526	1200.00	0
130.000	1038.96	1200.00	0
125.000	1533.55	1200.00	0
120.000	2286.10	1200.00	0
115.000	3443.91	1200.00	0
110.000	5246.18	1200.00	0
105.000	8086.78	1200.00	0
100.000	12623.4	1200.00	0
95.0000	19971.7	1200.00	0
90.0000	32055.0	1200.00	0
85.0000	52248.4	1200.00	0
80.0000	86582.7	1200.00	0
75.0000	146058.	1200.00	0
70.0000	251170.	1200.00	0
65.0000	440988.	1200.00	0
60.0000	791858.	1200.00	0
55.0000	1.456930E+06	1200.00	0
150.000	12.7974	1300.00	0
145.000	17.8811	1300.00	0
140.000	25.1737	1300.00	0
135.000	35.7232	1300.00	0
130.000	51.1203	1300.00	0
125.000	73.8044	1300.00	0
120.000	107.553	1300.00	0
115.000	158.296	1300.00	0
110.000	235.436	1300.00	0
105.000	354.098	1300.00	0
100.000	538.931	1300.00	0
95.0000	830.713	1300.00	0
90.0000	1297.94	1300.00	0
85.0000	2057.66	1300.00	0
80.0000	3313.34	1300.00	0
75.0000	5425.69	1300.00	0
70.0000	9047.24	1300.00	0
65.0000	15384.5	1300.00	0
60.0000	26721.3	1300.00	0
55.0000	47489.7	1300.00	0

EOF

Note, 0 is the same as 000 for the flag in the example above.

3.3 Stress Conversion Method

The default method, within NASALIFE, for converting a multiaxial stress load to an effective uniaxial stress is with the use of the Manson-McKnight method. With the use of the keyword, MNMD, the user can specify the Manson-McKnight method or the other available methods described in the

Multiaxial Fatigue Methods section. The keyword, MNMD, is placed on one line with the method keyword on the following line. The keywords for the methods are

blank line	Manson-McKnight method
SHAF	Modified Manson-McKnight method
SINE	Sines method
SWT	Smith-Watson-Topper method
RSIN	<i>R</i> -Ratio Sines method
EQVL	Effective method

3.4. Mission Loads

Finally, the mission loading conditions are added to the input file for NASALIFE. The loading information consists of time, temperature, and six components of stress.

The mission points are identified by the keywords, TIME, TEMP, S11, S22, S33, S12, S23, S31, and NULL. TIME corresponds to time in seconds. The final time in the mission is considered to be the mission duration and is used to calculate the fatigue lifetime (predicted cycles to failure x mission time). The keyword, TEMP, refers to the temperature in degrees Fahrenheit. Additionally, the keyword, TCON, will set the temperatures for the next mission to a constant. The stresses S11, S22, and S33 correspond to the normal stresses, σ_{xx} , σ_{yy} , and σ_{zz} , respectively. The stresses S12, S23, and S31 correspond to the shear stresses σ_{xy} , σ_{yz} , and σ_{xz} , respectively. All the stresses are in units of ksi.

Only those keywords that have data need to be used. An example is to use S11 only for a normal uniaxial case. The keyword NULL will ignore a column of data.

An example of typical mission loading data is provided below. Also, Figure 3 illustrates the stress, S22, with respect to time from the same mission loading data.

TIME	TEMP	S11	S22	S12
1	1250	0	-31	2
2	1250	0	-77	2
3600	1250	0	-140	0

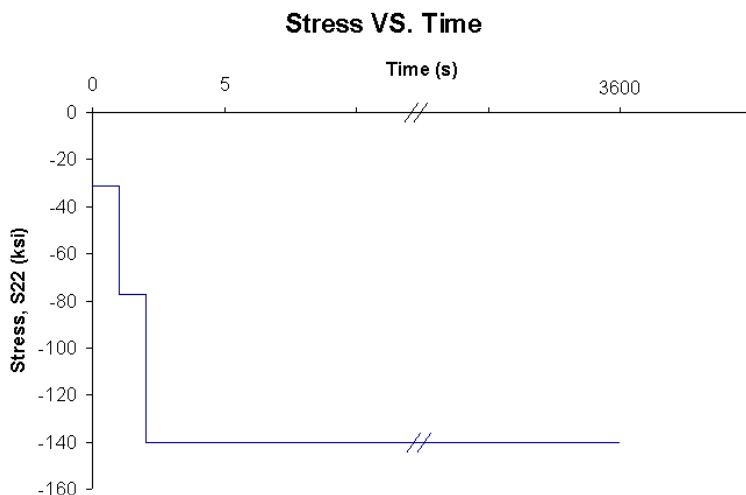


Figure 3.—A plot of stress, S22, with respect to time.

3.5. Input File

All the sections of the mission input file described are compiled into a single file. Optionally, the sections can be stored in separate files. With the use of the FILE command within the main input file the user can direct the main input file to the smaller files for the required data. As an example, a file containing rupture equation data may be created. For now, the rupture information file can be called testn.rupd. Any file name is acceptable. The file, testn.rupd, will contain the example provided previously, that is

```
RUPD
TITL
Example NASALIFE creep rupture equation data
TMLO TMHI STLO STHI C   SOFF  TMUL  TADD
1200  1300   55  150 20   2.00   1  459.67
PM
40
-15
-7
EOF
```

The following is an example of a mission input file for NASALIFE with the call for the rupture information from another file, that is, testn.rupd

```
PRIN
3 1 1 0 0 2 2 2 2 1

FILE
testn.rupd

LCF
TITL
Example NASALIFE LCF data
ARAT
1
FLIF SMAX FLAG TEMP
  1000 400 20  60
 10000 51 20
100000 50 121
  1000 300 0 300
 10000 21 0
100000 20 0
  1000 300 0 1000
 10000 21 0
100000 20 0
  1000 300 12 1300
 10000 11 10
100000 10 11
EOF

MATL
TITL
```

Example NASALIFE material file

IOP1 IOP2

1 1

TEMP M FLAG

60 .5 20

1300 .5 10

TEMP E K N V FLAG

60 30000 100 0 .3 20

1300 30000 100 0 .3 10

EOF

TIME TEMP S11 S22 S12

1 1250 0 -31 2

2 1250 0 -77 2

3600 1250 0 -140 0

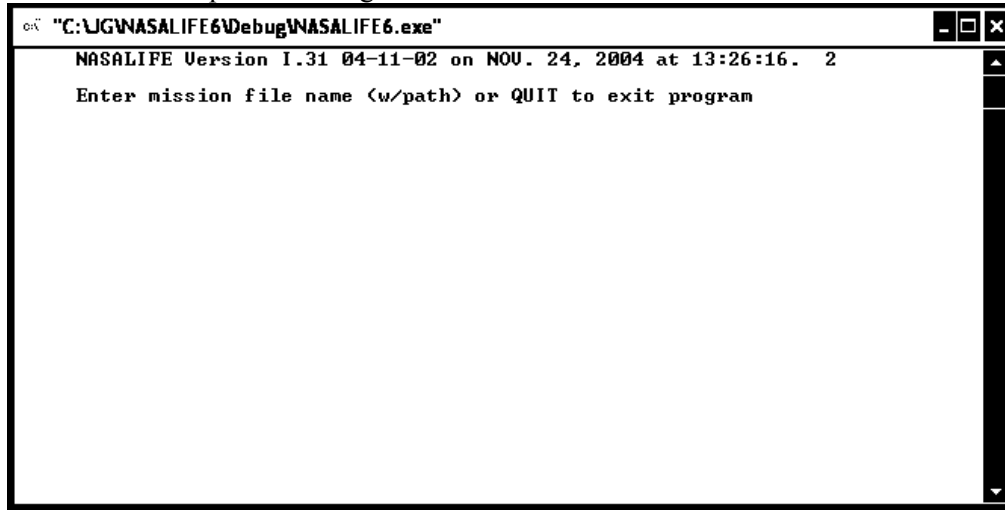
3.6. Keyword Definitions

KEYWORDS	DEFINITIONS
PRIN	Indicates which way the output is to be displayed. This must be the only key on a line. The next line will have 10 integer values. (see section 3.1)
ARAT	A-ratio used with LCF data.
TMF	The Thermal mechanical fatigue option: 1 Most damaging temperature 2 Maximum temperature 3 Average temperature
MNMD	mutiaxial material option ' ' Manson-McKnight (default) SHAF Modified Manson-McKnight SINE Sines SWT Smith Watson Topper RSIN R-Ratio Sines EQVL Effective
LCF	The LCF data follows this key.
LCFO	The old format LCF data follows this key.
MATL	The material data follows this key.
MATO	The old format material data follows this key.
RUPD	The rupture equation data follows this key.
RUPT	The rupture table data follows this key.
FILE	The next line is a filename to be read.
TIME	The mission time.
TEMP	The temperature in degrees Fahrenheit.
S11, S22, S33 S12, S23, S31	The six components of stress. The minimum input can be 1 stress component.
NULL	This will ignore a column of mission data.
XVIB	The mission mix fraction or percent usage the composite mission occurred relative to the overall mission.
SA11, SA22, SA33 SA12, SA23, SA31	The stress adder, these value are added to stress components

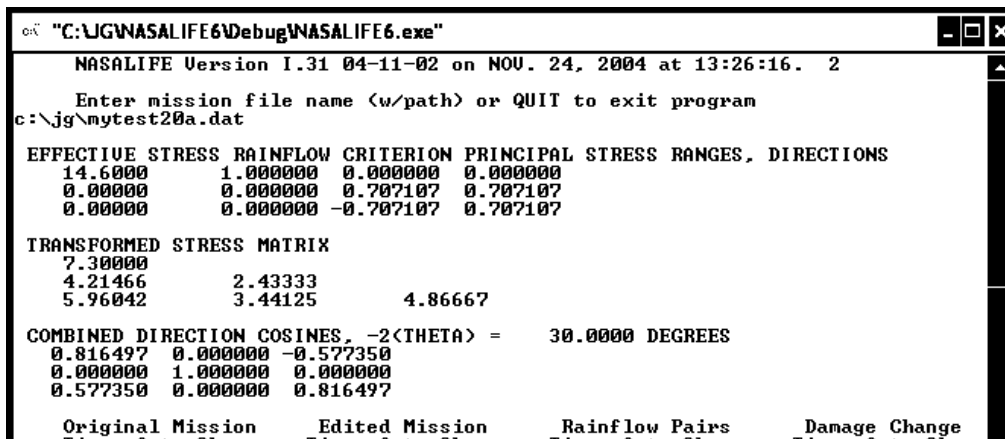
SM11, SM22, SM33 SM12, SM23, SM31	The stress multiplier, stress components are scaled by these
TMPA	The temperature adder or offset, this value is added to all temperatures.
TMPM	The temperature multiplier, all temperatures are scaled by this
TMEA	The time adder or offset. This value is added to all times.
TMEM	The time multiplier. All times are scaled by this.
FRUP, PRUP, TRUP	<p>The rupture Pesting data.</p> <p>if PRUP is positive</p> $RLIFE = RLIFE * 10. ** (FRUP + PRUP * TEMP)$ <p>if PRUP is negative</p> $RLIFE = RLIFE * (FRUP + PRUP * (TEMP - TRUP) * (TEMP - TRUP))$
FLCF, PLCF, TLCF	The LCF Pesting data. Note, these variables are read but not utilized by the program at this time. These may be incorporated in future versions of NASALIFE.
TSIG, TTEM, TTIM	The tolerances for stress, temperature, and time for rupture.
MXNI	The maximum number of increments per sub-cycle for rupture.

3.7. Executing NASALIFE

Upon executing NASALIFE the first terminal screen is



The full name of the mission file and its path is entered. If there is a need to terminate the program at this point then the command QUIT may be entered. Once the mission file is entered the program calculates the number of missions that can be accomplished under the given loading conditions. The image below illustrates a part of the output window one would observe when the PRIN command directs output to the terminal.



A simpler terminal output is displayed with the PRIN command directing output to a file. The resulting terminal display is shown below.


```

C:\JG\NASALIFE6\Debug\NASALIFE6.exe
NASALIFE Version I.31 04-11-02 on NOV. 24, 2004 at 13:43:10.111
Enter mission file name (w/path) or QUIT to exit program
c:\jg\mytest20a.dat

I need to create an output file
c:\jg\mytest20a.out
and there is already one in this directory,
Enter 'U' to use this file
Enter 'Q' to quit
u

      Time           Temperature           Mission Mix           Walker
      Min    Max      Min    Max      Fraction    Alt. Stress
      0.0    60.0    2000.0  2000.0      1.0        7.3
Mission stresses below rupture data
Non approved rupture data point used

Rupture Missions To Failure      72, Damage/Mission  1.384E-02,  54%
Fatigue Missions To Failure      85, Damage/Mission  1.179E-02,  46%
Combined Missions To Failure     39, Damage/Mission  2.563E-02, 100%

Output data is in file
c:\jg\mytest20a.out

Run program again? [N]

```

NASALIFE creates an output file that replaces the input file's extension with the extension of ".out". In the case an output file exists with the same name the program prompts the user to quit the run or overwrite the file with a new output file. The terminal window shows the output file's full path and name. Also, the user has the option of running the program again with the default value being to terminate the program.

3.8. Glossary of Flags

Section 3.8.1 lists the flags which can be printed out within NASALIFE and section 3.8.2 describes in more detail the meaning of those flags. Section 3.8.3 lists rupture flags and section 3.8.4 describes the rupture flags.

3.8.1. List of NASALIFE Output Flags (LCF)

- 1.a ZERO LIFE: Mission temperatures above material temperatures
- 1.b ZERO LIFE: Mission temperatures below material temperatures
- 1.c ZERO LIFE: Mission temperatures above and below material temperatures

- 2.a Mission temperatures above Walker exponent curve
- 2.a Mission temperatures below Walker exponent curve
- 2.c Mission temperatures above and below Walker curve

- 3.c High temperature extrapolated walker curve used
- 3.c Low temperature extrapolated walker curve used
- 3.c Low and high temperature extrapolated walker curve used

- 4.a Mission temperatures above material curves
- 4.b Mission temperatures below material curves
- 4.c Mission temperatures above and below material curves

- 5.a High temp extrapolated material curve used

- 5.b Low temp extrapolated material curve used
- 5.c Low and high temp extrapolated material curve used

- 6.a Mission temperatures above LCF curve
- 6.b Mission temperatures below LCF curve
- 6.c Mission temperatures above and below LCF curve

- 7.a High temp extrapolated LCF curve used
- 7.b Low temp extrapolated LCF curve used
- 7.c Low and high temp extrapolated LCF curve used

- 8.a High life extrapolated LCF curve used
- 8.b Low life extrapolated LCF curve used
- 8.c Low and high life extrapolated LCF curve used

- 9.a Pseudo stress extrapolation performed on life calculation
- 9.b ZERO LIFE: Walker stress extrapolation not permitted above LCF data

- 11. Non approved LCF curve point used

- 12. Low temperature extrapolation used

- 13.a These results may have a large step change in the mean stresses and fatigue life.
- 13.b ZERO LIFE: Shaft life mean stresses have a non-zero middle principal stress

- 14. The stress R-ratio less than -1 was reset to -1

- 15. Used default walker exponents. ($R < 0$, $M = 1$; $R \geq 0$, $M = .5$)

- 16.a Yield strength exceeded. Used stress amplitude (higher than Walker.)
- 16.b Yield strength exceeded. Used Walker stress (higher than alternating.)

3.8.2. Interpretation of NASALIFE Output Flags (LCF)

Flag No.

1. At least one of your mission points exceeds a temperature condition; other flags will be more specific. (Zero life)
2. You are outside of the range of Walker temperatures.
3. Your mission uses points on a temperature extrapolated Walker curve.
4. You are outside of the range of your material temperatures.
5. Your mission uses points on a temperature extrapolated material curve.
6. You are outside of the range of LCF temperatures.
7. Your mission uses points on a temperature extrapolated LCF curve.
8. Your mission uses points on a life extrapolated LCF curve.
9. Your Walker stress amplitude was:
 - a, lower than the lowest value supplied in your LCF curve (extrapolation to low stress is permitted)
 - b, higher than the highest value supplied in your LCF curve (Zero life)
10. Not used.
11. You are using material data flagged for special purposes.
12. Your mission contains points below room temperature.
- 13.a You experienced a mean stress shift.
- 13.b Your stress state is not applicable for shaft life, this is not a torsion controlled problem. (Zero life)
14. You have an R -ratio that is less than one (see section 2.3.2).
15. Your material file specified default Walker exponents.
16. Your alternating stress was greater than your yield strength (see section 2.3.2)

3.8.3. List of NASALIFE Output Flags (Rupture)

- 1.a Mission temperatures below rupture data
- 1.b Mission temperatures above rupture data
- 1.c Mission temperatures above and below rupture data

- 2.a High temperature extrapolated rupture data used
- 2.b Low temperature extrapolated rupture data used
- 2.c Low and high temperature extrapolated rupture data used

- 3.a High life extrapolated rupture data used
- 3.b Low life extrapolated rupture data used
- 3.c Low and high life extrapolated rupture data used

- 4.a Mission stresses below rupture data
- 4.b Mission stresses above rupture data
- 4.c Mission stresses above and below rupture data

- 5.a Non approved rupture data point used

3.8.4. Interpretation of NASALIFE Output Flags (Rupture)

Flag No.

- 1. You are outside of the range of rupture temperatures.
- 2. Your mission uses points on a temperature extrapolated rupture curve.
- 3. Your mission uses points on a life extrapolated rupture curve.
- 4. Your effective stress was:
 - a, lower than the lowest value supplied in your rupture curve (extrapolation to low stress is permitted)
 - b, higher than the highest value supplied in your rupture curve (Zero life)
- 5. You are using rupture data flagged for special purposes.

3.9. NASALIFE Output Example

An example of an output from NASALIFE is provided in this section. The lines have been numbered for this example so that the lines can be addressed to describe the individual output lines.

1 NASALIFE Version I.32 2005-02-04 on JAN. 13, 2005 at 14:46:13.993

2 WARNING: This code is subject to change.

3 The user is responsible for proper life methods.

4 Mission 1 in file

5 c:\jg\mytest18a.dat

6 User defined fatigue curves utilized.

7 Idealized LCF data table for MI SiC/SiC

8 Curve A-Ratio = 1.00000

9 Life (Cycles)	Stress (KSI)	Flag	Temperature	60.0
10 1000	400.0	20		
11 10000	51.0	20		
12 100000	50.0	121		

13 Life (Cycles)	Stress (KSI)	Flag	Temperature	300.0
14 1000	300.0	0		
15 10000	21.0	0		
16 100000	20.0	0		

17 Life (Cycles)	Stress (KSI)	Flag	Temperature	1000.0
18 1000	300.0	0		
19 10000	21.0	0		
20 100000	20.0	0		

21 Life (Cycles)	Stress (KSI)	Flag	Temperature	1300.0
22 1000	300.0	12		
23 10000	11.0	10		
24 100000	10.0	11		

25 Example NASALIFE material file

26 Curve Number = .000000E+00

27 Material Number = .000000E+00

28 Material Form = .000000E+00

29 ASTM Grain Size = .000000E+00

30 Specimen Orientation = .000000E+00

31 Specimen RKT = .000000E+00

32 Temp (°F)	Walker Exp	Temp Flag
33 60.0	.50	20
34 1300.0	.50	10

35 Temp (°F)	Modulus (KSI)	K (KSI)	N	Gnu	Temp Flag
36 60.0	30000.0	100.0	.00000	.30000	20
37 1300.0	30000.0	100.0	.00000	.30000	10

38 Conservative Walker mean stress model utilized

39 Time	Temp	XVIB	S11	S22	S33	S12	S23	S31
40 1.0	1250.0	1.000	.0	-31.0	.0	2.0	.0	.0
41 2.0	1250.0	1.000	.0	-77.0	.0	2.0	.0	.0

42 3600.0 1250.0 1.000 .0 -140.0 .0 .0 .0 .0
 43 Damaging temperature at maximum or minimum stress used in fatigue calculation
 44 Manson-McKnight Multiaxial Mean Stress model utilized
 45 Isothermal method used
 46 Low and high temperature extrapolated Walker curve used
 47 Low and high temperature extrapolated material curve used
 48 High temperature extrapolated LCF curve used
 49 Low life extrapolated LCF curve used
 50 Pseudo stress extrapolation performed on life calculation
 51 The stress *R*-ratio less than -1 was reset to -1

52 Temperature extremes of 1250.0 to 1250.0

53 Cycle	Time	Temperature	Stress	Walker	Calculated
54 Number	Min	Max	Min	Max	Alt
55 1	1.0	3600.0	1250.0	1250.0*	-140.0 -31.0 38.6 4423

56 * Indicates most damaging temperature.

57 Rupture Calculations

58 Time	Temp	Stress	Rupture Life	Delta Time	Rupture Damage
59 .0	1250.0	54.1	250195.	1.388889E-04	5.551218E-10
60 .0	1250.0	77.1	21677.9	1.388889E-04	1.576840E-09
61 .0	1250.0	79.0	17776.8	3.123264E-02	1.584792E-06
62 .1	1250.0	81.0	14616.5	3.123264E-02	3.513134E-06
63 .1	1250.0	83.0	12049.0	3.123264E-02	5.855685E-06
64 .1	1250.0	84.9	9957.53	3.123264E-02	8.694171E-06
65 .2	1250.0	86.9	8249.21	3.123264E-02	1.212506E-05
66 .2	1250.0	88.9	6850.25	3.123264E-02	1.626198E-05
67 .2	1250.0	90.8	5701.70	3.123264E-02	2.123852E-05
68 .3	1250.0	92.8	4756.40	3.123264E-02	2.721142E-05
69 .3	1250.0	94.8	3976.55	3.123264E-02	3.436425E-05
70 .3	1250.0	96.7	3331.69	3.123264E-02	4.291149E-05
71 .3	1250.0	98.7	2797.23	3.123264E-02	5.310338E-05
72 .4	1250.0	100.6	2353.27	3.123264E-02	6.523139E-05
73 .4	1250.0	102.6	1983.70	3.123264E-02	7.963437E-05
74 .4	1250.0	104.6	1675.40	3.123264E-02	9.670558E-05
75 .5	1250.0	106.5	1417.68	3.123264E-02	1.169007E-04
76 .5	1250.0	108.5	1201.82	3.123264E-02	1.407470E-04
77 .5	1250.0	110.5	1020.65	3.123264E-02	1.688533E-04
78 .6	1250.0	112.4	868.310	3.123264E-02	2.019219E-04
79 .6	1250.0	114.4	739.978	3.123264E-02	2.407615E-04
80 .6	1250.0	116.4	631.666	3.123264E-02	2.863019E-04
81 .7	1250.0	118.3	540.090	3.123264E-02	3.396111E-04
82 .7	1250.0	120.3	462.526	3.123264E-02	4.019134E-04
83 .7	1250.0	122.3	396.722	3.123264E-02	4.746110E-04
84 .8	1250.0	124.3	340.800	3.123264E-02	5.593072E-04
85 .8	1250.0	126.2	293.197	3.123264E-02	6.578334E-04
86 .8	1250.0	128.2	252.613	3.123264E-02	7.722785E-04
87 .8	1250.0	130.2	217.957	3.123264E-02	9.050221E-04
88 .9	1250.0	132.1	188.319	3.123264E-02	1.058773E-03
89 .9	1250.0	134.1	162.937	3.123264E-02	1.236607E-03
90 .9	1250.0	136.1	141.162	3.123264E-02	1.442018E-03
91 1.0	1250.0	138.0	122.460	3.123264E-02	1.678967E-03
92 1.0	1250.0	140.0	106.372	3.123264E-02	1.951941E-03
93 107.1	1250.0	140.0	106.372	106.164	1.00000

```

94 Rupture Ident
95 Example NASALIFE rupture data
96 Average rupture data used
97 Functional rupture data used
98 Rupture data valid from 1200.0 to 1300.0 °F
99     and from 55.0 to 150.0 KSI
100 Stress Offset 2.00000
101 Temperature Adder 459.670
102 Temperature Multiplier 1.00000
103 Larson-Miller Constant 20.0000 Polynomials
104 40.0000 -15.0000 -7.00000

105 Mission stresses below rupture data

106 Rupture Missions to Failure 512, Damage/Mission 1.952E-03, 90%
107 Fatigue Missions to Failure 4423, Damage/Mission 2.261E-04, 10%
108 Combined Missions to Failure 459, Damage/Mission 2.178E-03, 100%

```

Referring to the NASALIFE sample output above the individual output lines are described here. The numbers presented here refer to the line numbers above. The printout format is described, including how it is to be interpreted.

1. The name of the computer code is NASALIFE. The release number and the date of its release are as shown.
2. The technical contents in NASALIFE will be changed or added to as directed and with the appropriate documentations.
3. Use of this program does not insure proper life calculations. As noted, it is the user responsibility to have an understanding of the problem and its modeling. NASALIFE is a tool to assist in the modeling process.
- 4.–5. The load case number and the mission file with its path used for the run.
- 6.–24. The fatigue curve data used and its title.
- 25.–38. The material property data.
- 39.–42. The chronological mission mechanical and thermal loading data used in this run.
- 43.–45. Program message on options and data utilized for analysis.
- 46.–51. Flags which are discussed in section 3.8
52. The minimum and maximum temperature after the mission loading has been reduced to a simplified equivalent load by rainflow counting.
- 53.–55. The time, temperature, and stress for a cycle pair after the rainflow counting method has been applied.
56. The asterisk indicates the temperature used to determine the fatigue life. As per the message, it is the temperature where the most damage takes place.

Minor cycles which have a fatigue life greater than $1E7$ cycles are not printed out. The total number of minor cycles not printed noted in the output when they are present. This particular example does not have any suppressed minor cycles.

- 57.–92. These lines present the results of the rupture life calculation. The unit of time is hours.

- 93. The time where damage reaches one is always printed on a separate line. In this case the damage is less than one at the end of the mission. The time to damage of one is calculated using the last time point's stresses and temperature.

- 94.–104. The creep rupture data and other rupture related properties and settings are presented here.

- 105. This line has any creep rupture related flags.

- 106.–108. The life, damage per mission and percent of total damage for rupture, fatigue, and the combination are presented at the end of the output.

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Appendix A

Subroutine/Function	Description/Purpose	Called by Subroutine
IZTRAS	zeros out ATRASH (int.)	RDMISS, KEYLCF, KEYMAT, XXUSRM
KEYLCF	read in LCF curve	RDMISS
KEYMAT	read material property file in keyword format	RDMISS
KEYRPD	read rupture data in equation form	RDMISS
KEYRPT	read rupture data, tabular?	RDMISS
RDMISS	reads mission file	MAIN
RMDATA	rupture life from data	RMLIFE
RMLIFC	calculates time to rupture	MAIN
RMLIFE		RMLIFC
RMPRNF	print rupture tripped flags	XXPRNO
RMPRNO	print rupture life calculation information	MAIN
RMTABL	rupture life from tabular data	RMLIFE
SYDAHR	get date and time from system clock	XXPRNV
SYEXIT	siesta exit handler	MAIN, RDMISS, KEYLCF, KEYMAT, XXLIFC, RMLIFE, XXUSRM, XXUSRL, UTSFIL, SYFILE
SYFILE	siesta file operations	MAIN, RDMISS
SYLUIF	siesta UIF format line reader	XXUSRM, SYRUIF
SYPARS	parses a character string	SYLUIF
SYRDNB	read & strip leading blanks	MAIN, RDMISS, KEYLCF, KEYMAT, XXUSRL
SYRUIF	siesta UIF format file reader	RDMISS, KEYLCF, KEYMAT, XXUSRM, XXUSRL
SYSCON	sets siesta constants	MAIN
SYUCAS	converts character string to upper string	SYFILE, SYLUIF
UTJCB	calculates eigenvalues & eigenvectors of square symmetric matrix using Jacobi method	UTSPRN
UTMMPY	performs matrix multiplication	XXROT3, XXCRTP
UTRASH	sets an array to a 'TRASH' value	XXUSRL
UTSEFF	calculate effective stress	XXMSHF, RMLIFC, XXMSIN, XXMRSN, XXMEQV, XXMMMM
UTSFIL	sets siesta file codes	MAIN
UTSPRN	calculate principal stresses & direction vectors	XXMSHF, XXMSWT, XXCRTP
UTSRTA	sorts sets of FLT. data	UTSPRN
XXCRTP	life calculation	XXLIFC
XXDAMG	perform damage & multiaxial stress rainflow	XXLIFC
XXFLAG	flag adder	XXDAMG, RMDATA, RMTABL, XXINTR, XXWALK, XXLIFC
XXFLIP	reverses cycles based on temperature then original order	XXLIFC, XXSORT
XXINTR	linear temperature interpolation	XXSNSL, XXDAMG
XXLCFC	calculate LCF life from stress & temperature	XXPAIR
XXLIFC	life calculation	MAIN
XXMEQV	multiaxial mean stress, equivalent	XXMNMD
XXMINE	mission life calculation with Minor's fatigue damage rule	XXLIFC
XXMMMM	multiaxial mean stress, Manson-McKnight	XXMNMD
XXMNMD	convert multiaxial stresses to uniaxial	XXLIFC, XXDAMG, XXPAIR
XXMRSN	multiaxial mean stress, R ratio sines	XXMNMD
XXMSD	edits the mission	XXLIFC, XXXVIB
XXMSHF	multiaxial mean stress, shaft life Manson-McKnight	XXMNMD
XXMSIN	multiaxial mean stress, sines	XXMNMD
XXMSWT	multiaxial mean stress, Smith Watson Topper	XXMNMD
XXNXPT	finds the next rainflow point in a mission	XXRAIN
XXPAIR	evaluate the life for a mission pair	XXDAMG, XXSORT
XXPRNE	debug mission output	XXLIFC
XXPRNF	print tripped flags	XXPRNO
XXPRNV	prints xlife version information	MAIN, XXLIFC, XXPRNO
XXPRNO	print fatigue life calculation information	XXLIFC
XXRAIN	rainflows the mission	XXLIFC, XXXVIB
XXRDFL	reads ted zeh special title line	XXLIFC
XXROT3	rotates a stress matrix	XXMSWT
XXSNSL	converts an A ratio LCF curve to an A=INF curve	MAIN
XXSORT	sort mission/barry kalb damage replacement	XXLIFC
XXUSRL	read user LCF curve information	RDMISS
XXUSRM	read material property file	RDMISS
XXWALK	calculate Walker alternating stress	XXPAIR
XXWALP	emulates XXWALK for printout	XXPRNO
XXXSRT	sorts rainflowed life data	XXSORT
XXXVIB	adds XVIB & XBLOCK information, deletes small cycles	XXLIFC
ZTRAS	zeros out ATRASH (FLT.)	RDMISS, KEYLCF, KEYMAT, XXUSRM, XXUSRL

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13. ABSTRACT (Maximum 200 words) NASALIFE is a life prediction program for propulsion system components made of ceramic matrix composites (CMC) under cyclic thermo-mechanical loading and creep rupture conditions. Although the primary focus was for CMC components, the underlying methodologies are equally applicable to other material systems as well. The program references empirical data for low cycle fatigue (LCF), creep rupture, and static material properties as part of the life prediction process. Multiaxial stresses are accommodated by Von Mises based methods and a Walker model is used to address mean stress effects. Varying loads are reduced by the Rainflow counting method or a peak counting type method. Lastly, damage due to cyclic loading and creep is combined with Minor's Rule to determine damage due to cyclic loading, damage due to creep, and the total damage per mission and the number of potential missions the component can provide before failure.				
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